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Search for $B^\pm \to [K^\mp\pi^\pm]_D K^\pm$ and upper limit on the $b \to u$ amplitude in $B^\pm \to DK^\pm$

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We search for $B^{\pm} \to [K^{\mp}\pi^{\pm}]_D K^{\pm}$ decays, where $[K^{\mp}\pi^{\pm}]_D$ indicates that the $K^{\mp}\pi^{\pm}$ pair originates from the decay of a D^0 or $\overline{D}^0$. Results are based on 120×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at SLAC. We set an upper limit on the ratio

$$\mathcal{R}_{K\pi} \equiv \frac{(\Gamma(B^+ \to [K^-\pi^+]_D K^+) + \Gamma(B^- \to [K^+\pi^-]_D K^-))}{(\Gamma(B^+ \to [K^+\pi^-]_D K^+) + \Gamma(B^- \to [K^-\pi^+]_D K^-))} < 0.026 \quad (90\% \text{ C.L.}).$$

This constrains the amplitude ratio $r_B \equiv |A(B^- \to \overline{D}^0 K^-)/A(B^- \to D^0 K^-)| < 0.22$ (90% C.L.), consistent with expectations. The small value of r_B favored by our analysis suggests that the determination of the CKM phase γ from $B \to DK$ will be difficult.

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Following the discovery of *CP* violation in B-meson decays and the measurement of the angle β of the unitarity triangle [1] associated with the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, focus has turned towards the measurements of the other angles α and γ. The angle γ is $\arg(-V_{ub}^* V_{ud}/V_{cb}^* V_{cd})$, where V_{ij} are CKM matrix elements; in the Wolfenstein convention [2], $\gamma = \arg(V_{ub}^*)$.

Several proposed methods for measuring γ exploit the interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$ (Fig. 1) which occurs when the D^0 and the $\overline{D}^0$ decay to common final states, as first suggested in Ref. [3].

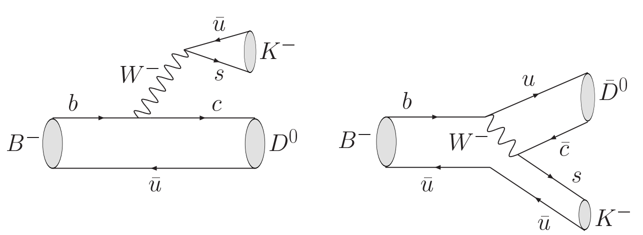

FIG. 1: Feynman diagrams for $B^- \to D^0 K^-$ and $\overline{D}^0 K^-$. The latter is CKM- and color-suppressed with respect to the former.

Following the proposal in Ref. [4], we search for $B^- \to \tilde{D}^0\ K^-$ followed by $\tilde{D}^0\ \to K^+\pi^-$, as well as the charge conjugate sequence, where the symbol $\tilde{D}^0$ indicates either a D^0 or a $\overline{D}^0$. Here the favored B decay followed by the doubly CKM-suppressed D decay interferes with the suppressed B decay followed by the CKM-favored D decay. We use the notation $B^- \to [h_1^+ h_2^-]_D h_3^-$ (with each $h_i = \pi$ or K) for the decay chain $B^- \to \tilde{D}^0\ h_3^-$, $\tilde{D}^0\ \to h_1^+ h_2^-$. We also refer to h_3 as the bachelor π or K. Then, ignoring D mixing,

$$\mathcal{R}_{K\pi}^{\pm} \equiv \frac{\Gamma([K^{\mp}\pi^{\pm}]_D K^{\pm})}{\Gamma([K^{\pm}\pi^{\mp}]_D K^{\pm})} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\pm\gamma + \delta),$$

where

$$r_B \equiv \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|, \quad \delta \equiv \delta_B + \delta_D,$$

$$r_D \equiv \left| \frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} \right| = 0.060 \pm 0.003 \text{ [5]},$$

and δ_B and δ_D are strong phase differences between the two B and D decay amplitudes, respectively. The expression for $\mathcal{R}_{K\pi}^{\pm}$ neglects the tiny contribution to the $[K^{\pm}\pi^{\mp}]_D K^{\pm}$ mode from the color suppressed B-decay followed by the douby-CKM suppressed D-decay.

Since r_B is expected to be of the same order as r_D, *CP* violation could manifest itself as a large difference between $\mathcal{R}_{K\pi}^{+}$ and $\mathcal{R}_{K\pi}^{-}$. Measurements of $\mathcal{R}_{K\pi}^{\pm}$ are not sufficient to extract γ, since these two quantities are functions of three unknowns: γ, r_B, and δ. However, they can be combined with measurements for other $\tilde{D}^0$ modes to extract γ in a theoretically clean way [4].

The value of r_B determines, in part, the level of interference between the diagrams of Fig. 1. In most techniques for measuring γ, high values of r_B lead to better sensitivity. Since $\mathcal{R}_{K\pi}^{\pm}$ depend quadratically on r_B, measurements of $\mathcal{R}_{K\pi}^{\pm}$ can constrain r_B. In the Standard Model, $r_B = |V_{ub}V_{cs}^*/V_{cb}V_{us}^*|\ F_{cs} \approx 0.4\ F_{cs}$, and $F_{cs} < 1$ accounts for the additional suppression, beyond that due to CKM factors, of $B^- \to \overline{D}^0 K^-$ relative to $B^- \to D^0 K^-$. Naively, $F_{cs} = \frac{1}{3}$, which is the probability for the color of the quarks from the virtual W in $B^- \to \overline{D}^0 K^-$ to match that of the other two quarks; see Fig. 1. Early estimates gave $F_{cs} \approx 0.22$ [6], leading to $r_B \approx 0.09$; however, recent measurements [7] of color suppressed $b \to c$ decays ($B \to D^{(*)} h^0$; $h^0 = \pi^0, \rho^0, \omega, \eta, \eta'$) suggest that F_{cs}, and therefore r_B, could be larger, *e.g.*, $r_B \approx 0.2$ [8]. A study by the Belle collaboration of $B^{\pm} \to \tilde{D}^0 K^{\pm}$, $\tilde{D}^0 \to K_S\pi^+\pi^-$, favors a large value of r_B: $r_B = 0.26^{+0.11}_{-0.15}$ [9].

Our results are based on 120×10^6 $\Upsilon(4S) \to B\overline{B}$ decays, corresponding to an integrated luminosity of 109 fb^{-1}, collected between 1999 and 2003 with the *BABAR* detector [10] at the PEP-II B Factory at SLAC. A 12 fb^{-1} off-resonance data sample, with a CM energy 40 MeV below the $\Upsilon(4S)$ resonance, is used to study continuum events, $e^+e^- \to q\bar{q}$ ($q = u, d, s$, or c).

The event selection was developed from studies of simulated $B\overline{B}$ and continuum events, and off-resonance data. A large on-resonance data sample of $B^- \to D^0\pi^-$,

$D^0 \to K^-\pi^+$ events was used to validate several aspects of the simulation and analysis procedure. We refer to this mode and its charge conjugate as $B \to D\pi$.

Kaon and pion candidates in $B^\pm \to [K\pi]_D K^\pm$ must satisfy K or π identification criteria that are typically 90% efficient, depending on momentum and polar angle. Misidentification rates are at the few percent level. The invariant mass of the $K\pi$ pair must be within 18.8 MeV (2.5σ) of the mean reconstructed D^0 mass. The remaining background from other $B^\pm \to [h_1 h_2]_D h_3^\pm$ modes is eliminated by removing events where any $h_i^+ h_j^-$ pair, with any particle-type assignment except for the signal hypothesis for the $h_1 h_2$ pair, is consistent with $\tilde{D}^0$ decay. We also reject B candidates where the $\tilde{D}^0$ paired with a π^0 or $\pi^\pm$ in the event is consistent with $D^* \to D\pi$ decay.

After these requirements, backgrounds are mostly from continuum, mainly $e^+e^- \to c\bar{c}$, with $\bar{c} \to \overline{D}{}^0 \to K^+\pi^-$ and $c \to D \to K^-$. These are reduced with a neural network based on nine quantities that distinguish continuum and $B\overline{B}$ events: (i) A Fisher discriminant based on the quantities $L_0 = \sum_i p_i$ and $L_2 = \sum_i p_i \cos^2\theta_i$ calculated in the CM frame. Here, p_i is the momentum and θ_i is the angle with respect to the thrust axis of the B candidate of tracks and clusters not used to reconstruct the B. (ii) $|\cos\theta_T|$, where θ_T is the angle in the CM frame between the thrust axes of the B and the detected remainder of the event. (iii) $\cos\theta_B$, where θ_B is the polar angle of the B in the CM frame. (iv) $\cos\theta_D^K$ where θ_D^K is the decay angle in $\tilde{D}^0 \to K\pi$, *i.e.*, the angle between the direction of the K and the line of flight of the $\tilde{D}^0$ in the $\tilde{D}^0$ rest frame. (v) $\cos\theta_B^D$, where θ_B^D is the decay angle in $B \to \tilde{D}^0 K$. (vi) the difference ΔQ between the sum of the charges of tracks in the $\tilde{D}^0$ hemisphere and the sum of the charges of the tracks in the opposite hemisphere excluding the tracks used in the reconstructed B. For signal, $\langle \Delta Q \rangle = 0$, while for the $c\bar{c}$ background $\langle \Delta Q \rangle \approx \frac{7}{3} \times Q_B$, where Q_B is the B candidate charge. The ΔQ RMS is 2.4. (vii) $Q_B \cdot Q_K$, where Q_K is the sum of the charges of all kaons not in the reconstructed B. Many signal events have $Q_B \cdot Q_K \leq -1$, while most continuum events have no kaons outside of the reconstructed B, and hence $Q_K = 0$. (viii) the distance of closest approach between the bachelor track and the trajectory of the $\tilde{D}^0$. This is consistent with zero for signal events, but can be larger in $c\bar{c}$ events. (ix) the existence of a lepton (e or μ) and the invariant mass ($m_{K\ell}$) of the lepton and the bachelor K. Continuum events have fewer leptons than signal events. Moreover, most leptons in $c\bar{c}$ events are from $D \to K\ell\nu$, where K is the bachelor kaon, so that $m_{K\ell} < m_D$.

The neural net is trained with simulated continuum and signal events. We find agreement between the distributions of all nine variables in simulation and in control samples of off-resonance data and of $B \to D\pi$. The neural net requirement is 66% efficient for signal, and rejects 96% of the continuum background. An additional requirement, $\cos\theta_D^K > -0.75$, rejects 50% of the remaining $B\overline{B}$ backgrounds and is 93% efficient for signal.

A B candidate is characterized by the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(\frac{s}{2} + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - p_B^2}$ and energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where E and p are energy and momentum, the asterisk denotes the CM frame, the subscripts 0 and B refer to the $\Upsilon(4S)$ and B candidate, respectively, and s is the square of the CM energy. For signal events $m_{\rm ES} = m_B$ within the resolution of about 2.5 MeV, where m_B is the known B mass.

We require ΔE to be within 47.8 MeV (2.5σ) of the mean value of -4.1 MeV found in the $B \to D\pi$ control sample. The yield of signal events is extracted from a fit to the $m_{\rm ES}$ distribution of events satisfying all of the requirements discussed above.

Our selection includes contributions from backgrounds with $m_{\rm ES}$ distributions peaked near m_B (peaking backgrounds). We distinguish those with a real $\tilde{D}^0 \to K^\mp\pi^\pm$ and those without, *e.g.*, $B^- \to h^+h^-h^-$. The latter are estimated from events with $K^\mp\pi^\pm$ mass in a sideband of the $\tilde{D}^0$. The former are from $B^- \to D^0\pi^-$, followed by the CKM-suppressed decay $D^0 \to K^+\pi^-$, with the bachelor π misidentified as a K. These are estimated as $N_{peak}^D = r_D^2 N_{D\pi}$, where $N_{D\pi}$ is the number of observed $B \to D\pi$ events with the π misidentified as a K. The technique used to measure $N_{D\pi}$ is described below. Studies of simulated $B\overline{B}$ events indicate that other peaking background contributions are negligible.

Because of the small number of events, we combine the B^+ and B^- samples. We define the quantity

$$\mathcal{R}_{K\pi} \equiv \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)},$$

$$\mathcal{R}_{K\pi} = \frac{\mathcal{R}_{K\pi}^+ + \mathcal{R}_{K\pi}^-}{2} = r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma\cos\delta,$$

assuming no CP violation in $[K^\mp\pi^\pm]_D K^\mp$.

We determine $\mathcal{R}_{K\pi} = c N_{sig}/N_{DK}$, where N_{sig} is the number of $B^\pm \to [K^\mp\pi^\pm]_D K^\pm$ signal events and N_{DK} is the number of $B^\pm \to [K^\pm\pi^\mp]_D K^\pm$ events, a mode which we denote by $B \to DK$. Most systematic uncertainties cancel in the ratio. The factor $c = 0.93 \pm 0.04$, determined from simulation, accounts for a difference in the event selection efficiency between the signal mode and $B \to DK$. This difference is mostly due to a correlation between the efficiencies of the $\cos\theta_D^K$ requirement and the $\tilde{D}^0$ veto constructed using the bachelor track and the oppositely-charged track in the $[K\pi]$ pair. This correlation depends on the relative sign of the kaon and the bachelor track, and is different in the two modes.

The value of $\mathcal{R}_{K\pi}$ is obtained from a simultaneous unbinned maximum likelihood fit to four $m_{\rm ES}$ and three ΔE distributions. These distributions are used to extract the parameters needed to calculate $\mathcal{R}_{K\pi}$ (*e.g.*, N_{sig}) or to

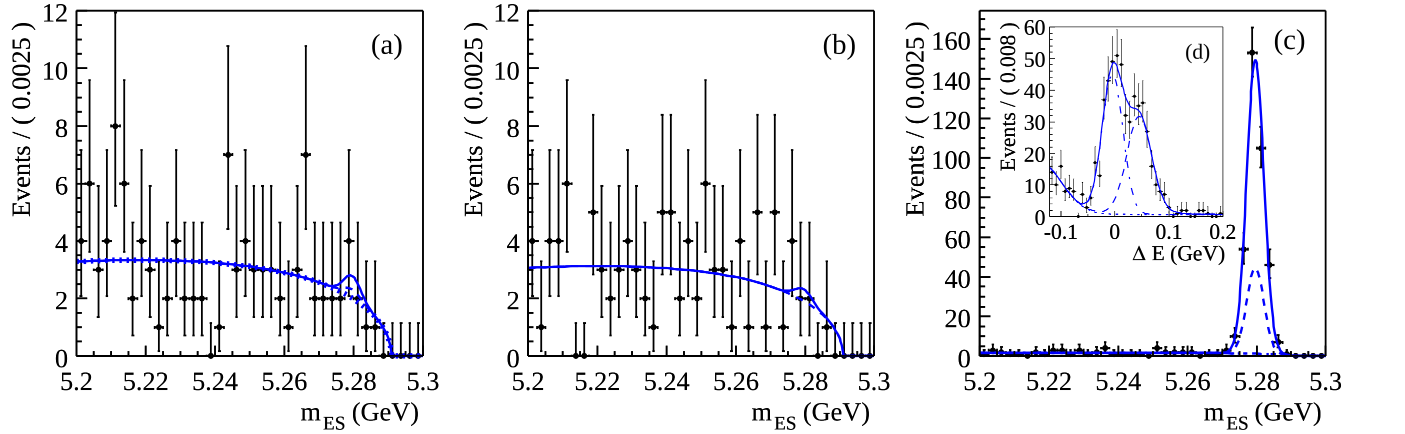

FIG. 2: m_{ES} distributions for (a) signal ($[K^{\mp}\pi^{\pm}]_D K^{\pm}$) candidates, (b) candidates from the $\tilde{D}^0$ sideband, and (c) $B \to DK$ candidates. The $\tilde{D}^0$ sideband selection uses a $K^{\mp}\pi^{\pm}$ invariant mass range 2.72 times larger than the signal selection. (d) ΔE distribution for $B \to DK$ candidates; the peak centered at ≈ 0.05 GeV is from $B \to D\pi$. The superimposed curves are described in the text. In (c), the dashed Gaussian centered at m_B represents the $B \to D\pi$ contribution estimated from (d).

constrain the shapes of other distributions. The likelihood is expressed directly in terms of $\mathcal{R}_{K\pi}$.

The m_{ES} distribution for signal candidates is fit to the sum of a threshold background function and a Gaussian centered at m_B. The number of events in the Gaussian is $N_{sig} + N^{D}_{peak} + N^{hhh}_{peak}$, where N^{D}_{peak} and N^{hhh}_{peak} are the number of peaking background events with and without a real $\tilde{D}^0$, respectively. The Gaussian parameters are constrained by the fit to the m_{ES} distribution of $B \to DK$ events. The shape of the threshold function is constrained by fitting the m_{ES} distribution of candidates in a sideband of ΔE ($-125 < \Delta E < 200$ MeV, excluding the signal region). The m_{ES} distribution for events passing all signal requirements, but with $K^{\mp}\pi^{\pm}$ mass in the sideband of the $\tilde{D}^0$ is fit in the same manner. We estimate N^{hhh}_{peak} from the Gaussian yield of this last fit, accounting for the different sizes of the signal and sideband $\tilde{D}^0$ mass ranges. The m_{ES} distributions for signal and $\tilde{D}^0$ sideband candidates are shown in Fig. 2a,b.

The m_{ES} distribution for $B \to DK$ candidates with $|\Delta E + 4.1\ \mathrm{MeV}| < 47.8$ MeV (see Fig. 2c) is also fit to a Gaussian and a threshold function. The number of events in the Gaussian is $N_{DK} + N_{D\pi}$, where, as previously defined, N_{DK} is the number of $B \to DK$ events and $N_{D\pi}$ is the number of $B \to D\pi$ events with the bachelor π misidentified as a K. The ratio $N_{DK}/N_{D\pi}$ is obtained by fitting the ΔE distribution for $B \to DK$ candidate events with $m_{\mathrm{ES}} > 5.27$ GeV (see Fig. 2d). This is modeled as the sum of a combinatoric background function, a double-Gaussian for the $B \to D\pi$ background, and a Gaussian for the $B \to DK$ signal. The parameters of the Gaussians in the ΔE fit are constrained from fits to the ΔE distributions of well-identified $B \to D\pi$ events with the bachelor π assumed to be a π or a K.

We find $\mathcal{R}_{K\pi} = (4 \pm 12) \times 10^{-3}$, consistent with zero. The number of signal, normalization, and peaking background events are $N_{sig} = 1.1 \pm 3.0$, $N_{DK} = 261 \pm 22$, $N^{D}_{peak} = r_D^2 N_{D\pi} = 0.38 \pm 0.07$, and $N^{hhh}_{peak} = 0.4 \pm 1.1$. The uncertainties are mostly statistical. From the likelihood, we set a Bayesian limit $\mathcal{R}_{K\pi} < 0.026$ at the 90% confidence level (C.L.), assuming a constant prior probability for $\mathcal{R}_{K\pi} > 0$ (see Fig. 3).

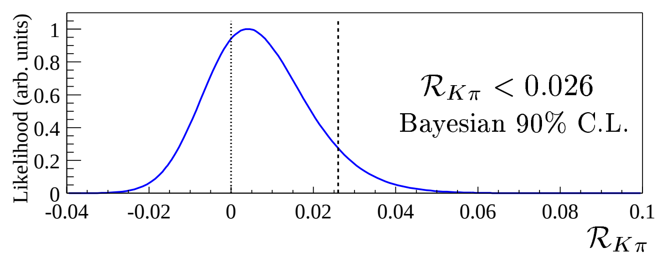

FIG. 3: Likelihood as a function of $\mathcal{R}_{K\pi}$. The integral for $0 < \mathcal{R}_{K\pi} < 0.026$ is 90% of the integral for $\mathcal{R}_{K\pi} > 0$.

In Fig. 4 we show the dependence of $\mathcal{R}_{K\pi}$ on r_B, together with our limit. This is shown allowing a $\pm 1\sigma$ variation on r_D, for the full range $0° - 180°$ for γ and δ, as well as with the restriction $48° < \gamma < 73°$ suggested by global CKM fits [11]. The least restrictive limit on r_B is computed assuming maximal destructive interference: $\gamma = 0°, \delta = 180°$ or $\gamma = 180°, \delta = 0°$. This limit is $r_B < 0.22$ at 90% C.L.

In summary, we find no evidence for $B^{\pm} \to [K^{\mp}\pi^{\pm}]_D K^{\pm}$. We set a 90% C.L. limit on the ratio $\mathcal{R}_{K\pi}$ of rates for this mode and the favored mode $B^{\pm} \to [K^{\pm}\pi^{\mp}]_D K^{\pm}$. Our limit is $\mathcal{R}_{K\pi} < 0.026$ at 90% C.L. With the most conservative assumption on the values of γ and of the strong phases in the B and D decays, this results in a limit on the ratio of the magnitudes of the $B^- \to \overline{D}^0 K^-$ and $B^- \to D^0 K^-$ amplitudes $r_B < 0.22$ at 90% C.L. Our analysis suggests that r_B is

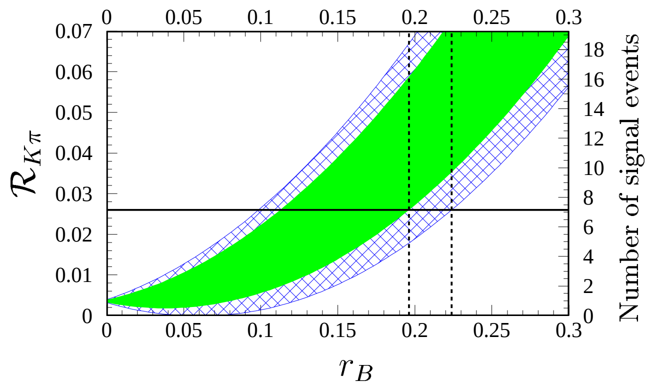

FIG. 4: Expectations for $\mathcal{R}_{K\pi}$ and N_{sig} *vs.* r_B. Filled-in area: allowed region for any value of δ, with a $\pm 1\sigma$ variation on r_D, and $48^\circ < \gamma < 73^\circ$. Hatched area: additional allowed region with no constraint on γ. The horizontal line represents the 90% C.L. limit $\mathcal{R}_{K\pi} < 0.026$. The dashed lines are drawn at $r_B = 0.196$ and $r_B = 0.224$. They represent the 90% C.L. upper limits on r_B with and without the constraint on γ.

smaller than the value reported by the Belle collaboration, $r_B = 0.26^{+0.11}_{-0.15}$ [9], but given the uncertainties the two results are not in disagreement. A small value of r_B will make it difficult to measure γ with other methods [3][12] based on $B \to \tilde{D}K$.

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